USDA Wind/Hybrid Research Laboratory Controls Development

Eric D. Eggleston and R. Nolan Clark
USDA - Agricultural Research Service
Wind/Hybrid Research Laboratory
Bushland, Texas

Wind turbines and diesel generator sets have operated independently to provide electric power for a number of years. However, there is a desire to combine them into a single system. Controls for such a system had to be constructed for the USDA Wind/Hybrid Research Laboratory (WHRL), Bushland, Texas[1]. The experience gained from this effort may be instructive to others interested in constructing similar hybrid systems.

The initial WHRL configuration consisted of an AOC 15/50[2] wind turbine, a Catepillar 3304PCNA, 49kW diesel generator, three motor loads, and a dual-duty load bank for village load simulation and controlled dumping of excess wind power. Figure 1 shows the configuration.

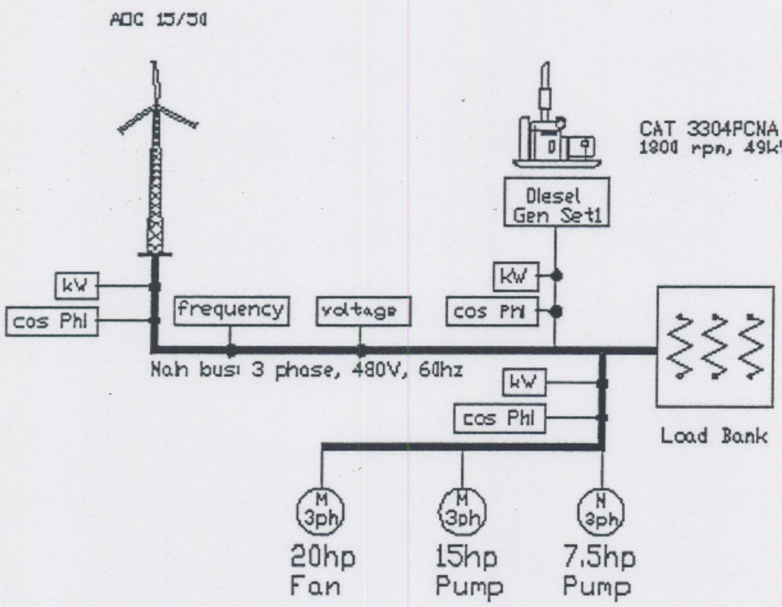

Figure 1: Initial Configuration, simplified

---

[1] Contribution from USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX 79012 in cooperation with the Alternative Energy Institute, West Texas A&M University, Canyon, TX.

[2] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

Running a 40kW constant village load, installed wind penetration is 125% (rated wind power/village load). Instantaneous penetration can be as high as 200% because the turbine can reach over 80kW for short periods. The diesel runs continuously and only shuts down for system errors or operator commands. There are only a few operational states, as shown in Figure 2.

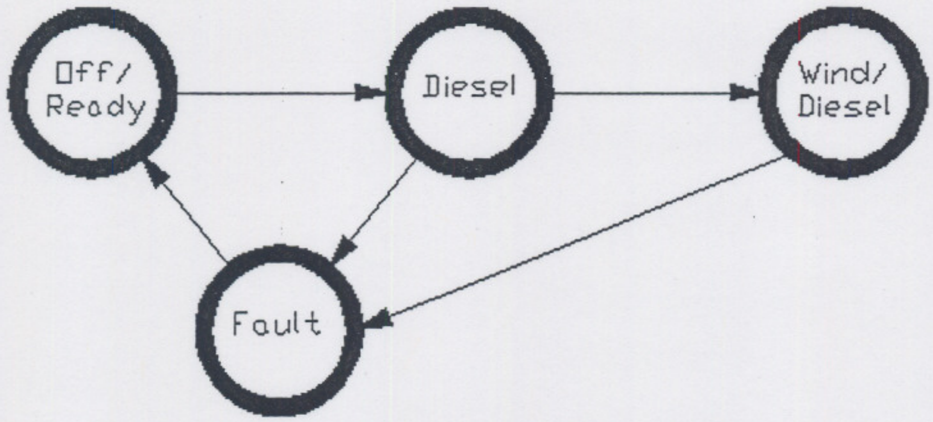

Figure 2: Operating State Diagram

The wind/hybrid system had only two operational modes:
1. Diesel only - diesel meets the entire load under droop frequency control.
2. Wind/Diesel - load is shared under hybrid load balancer/droop operation.

Diesel Only:
Diesel only operation is no different than normal engine generation. The governor adjusts the fuel flow to the engine to keep the rpm, therefore frequency, stable near 60hz -- much like a car's cruise control. In droop operation, the frequency output of the diesel depends on the load required of it. More load, slightly less frequency. For our CAT 3304PCNA, 49kW generator the linear droop is almost 2hz from no load to full load.

Wind/Diesel:
Wind/Diesel operation occurs when the wind turbine shares the load with the diesel. Frequency control must be shared between the diesel governor and the fuzzy logic load balancer frequency control in droop operation. When large amounts of wind power are available, the diesel is throttled back to the minimum load setting in the control program -- zero kilowatts, in our case. If this does not balance power, a progressive deferable balancer load is switched on, to adjust power demand up to meet the available supply. Two items control power balance and frequency: the diesel governor brings the frequency up, while the balancer load brings it down. Wind power becomes the preferred power supply, when available, since no fuel costs are incurred. Diesel power is used to fill the gap between village demand and wind power supply.

Wind/diesel operation requires keeping power supply and demand balanced, on the fly, with a computer controlled, progressive load. The steps of this balancer load are actuated according to several rules. The first rule is to maintain the operator's minimum power setting for the diesel. Load is added to bring the diesel up to the designated minimum.

Next come the droop mode operational rules. The frequency error (FE) is calculated by subtracting the current frequency measurement from the desired frequency pre-set. Our load balancer center frequency was 60.4hz. The change in frequency (FC) is calculated by subtracting the current frequency measurement from the last frequency measurement. Both the FE and FC may be multiplied by input gains, set in the controller, before being used as inputs to a fuzzy logic map like the following:

FE\FC	+0.8	+0.4	+0.2	+0.1	0	-0.1	-0.2	-0.4	-0.8
+4	-96	-48	-24	-12	-6	-6	-3	-1	-3
+2	-48	-24	-12	-6	-6	-3	-1	-3	1
+1	-24	-12	-6	-3	-3	-1	-1	1	3
+0.5	-12	-6	-3	-1	-1	-0.5	1	3	6
0	-6	-6	-3	-0.2	0	0.2	3	6	6
-0.5	-6	-3	-1	0.5	1	1	3	6	12
-1	-3	-1	1	1	3	3	6	12	24
-2	-1	3	1	3	6	6	12	24	48
-4	3	1	3	6	6	12	24	48	96

The field selected from this table is then multiplied by a pre-set output gain and combined with the minimum diesel load level rule output to determine the appropriate balancer load level for the next time step. This time interval between control commands must be at least as long as the time required for a new frequency sample.

Conflicts between the balancer load control and the diesel governor result in two undesirable tendencies: back-driving the diesel below minimum load, or dumping diesel generated power. To avoid these, the diesel governor must be adjusted so that the diesel becomes unloaded at about the same frequency that the dump load starts actuating. With a high, gusty wind and the system control half a second behind reality, one can always expect short bursts of diesel back-driving and/or dumping of diesel power. With proper adjustment, conflicts and dumped diesel energy can be minimized.

Only 9 faults were included in the control program which shut down the entire system in case of error. The diesel had it's own microprocessor to handle the four engine errors: overspeed, overcrank (failure to start), low oil pressure, and high coolant temperature. On any of these errors the system shuts down.

Since our load bank performs dual-duty as part of the village load simulator and as the "dump" load balancer to keep the frequency stable, any problem with it means loss of village load, loss of control over balancing wind power, and risk of load bank resistors burning out. There are three load bank errors that cause system shutdown: high intake air temperature, low pressure (no fan air flow to cool the resistors), and high exhaust air temperature. There are two additional, system wide shut down errors: over/under voltage and over/under frequency.

During our first trial of the system, a frequency error caused a shut down after 31 minutes and 4 seconds of operation with our turbine near full power in a gusty wind. Our system control was making balancer load level decisions every 100 miliseconds. We later realized that our frequency sensor only gave a new sample every 400 miliseconds. Because of this, the frequency control became unstable and caused the shut down. Balancer load decisions were slowed to once every 400 miliseconds.

The system sustained damage to the wind turbine controller as a result of the error shut-down. We had naively thought that telling the diesel to shut off and de-energizing all the contactors in the system was appropriate. When disconnected, the turbine went through an emergency stop, as it would with a blackout when grid inter-tied. However, the turbine's generator still had a field trying to collapse -- with nowhere to go. The result was a very high voltage spike on the turbine side which blew a surge suppressor, a main fuse, and a few components and traces off the controller board's power supply section. Repairs and error handling changes were required before further operation.

Error handling was changed to leave the load connected and increase the load bank to maximum; then, tell the diesel and turbine to shut off, by way of their respective controllers. This is analogous to putting your car in fourth gear at a stop sign and letting the clutch out. This change required new control wires and relays for each turbine.

We tried to add our Enertech 44/40 turbine, which required a soft-starter as our 49kW diesel would not be capable of handling the transient of hard-starting the 40kW turbine. In the process of installing the soft-starter on the turbine we encountered several issues:

First, read the instructions for the turbine and starter throughly. The soft start required that any power factor correction capacitors not be on the generator side of the unit. Also, make sure you know which capacitors you are looking at -- power factor correction capacitors, or dynamic brake capacitors.

Second, if the soft-starter (which is made to conduct current to and from the generator all the time) has any type of error, it will shut off the turbine's generator -- without the turbine controller knowing anything about it. This causes the turbine to lose load and overspeed until the safety system works, or the turbine falls apart. Fixing this required that the starter be placed in parallel with a delay contactor so that the starter is switch out of the system once the starting ramp-up has been completed.

Third, make sure you don't in advertently switch out the dynamic brake. With the dynamic brake connections on the wrong side of the parallel contactor, it never operates. We found this out 6 months later when the mechanical brake failed from over-use. It's a messy, stinky job to replace fried wind turbine brake disks. Better to have an operational dynamic brake, as intended.

Fourth, electronic turbine soft-starters may distort the AC wave form enough to destroy frequency measurements derived from counting zero voltage crosses. It is possible that, during starter ramp-up, the tail of each half cycle may be clipped, hovering near zero and causing the frequency transducer to see high phantom frequency -- which then causes a high frequency error shut down of the whole system. Counting shaft revolutions of a synchronous condenser or diesel may be the best way to avoid transients from distorting frequency measurements. In addition, if the frequency transducer fails, the system control is forced to shut down the entire system because no frequency is being measured. Therefore, frequency transducers become critical components for control of the system with wind power included.

We have identified a number of critical control parameters: minimum diesel power, diesel governor setting, frequency transducer sampling and system decision rate, the fuzzy logic control map, input gains for frequency error (FE) and frequency change (FC), and the fuzzy logic map output gain. All the gains could be eliminated from the control program and the fuzzy logic map manipulated directly, but it becomes harder to iterate toward optimal values. To pick the right settings in plush academic, deterministic style; one would need to do quite a bit of dynamic modeling with time constants, inertias, and lots of other information that almost no manufacturer can quote, and which require a large effort to determine experimentally. Or, you can build the system, find a quick sampling frequency transducer, guess at the gains, and calculate & iterate until the system is optimized and running very well. We followed the latter method.

It does help to know about effects and inter-relationships. Because of the larger inertias of diesels and wind turbines in larger systems, they react more slowly to changes in load or wind power. Likewise, smaller systems react more quickly and require faster controls. With our 49kW diesel and 50kW turbine system, a 400ms reaction time works well in mild conditions, but is too slow to handle violent conditions. In harsh conditions, with our rather droopy diesel, frequency swings from 59 to 61Hz do occur. As previously mentioned, short term back driving of the diesel and dumping of diesel power is another undesirable result. Computer control can be done much faster without trouble, but a faster, more robust frequency transducer is required.

While operating over 100% penetration, the frequency does tend to oscillate with a period of 2 to 3 seconds and similar trends have been observed in other hybrid systems within the wind/diesel literature. By observation, each parameter seems to have an optimal value. With each gain set too high or low, frequency swings appear to get worse. Flatter diesel governor droop would substantially reduce frequency swings. And the control time step and decision rate probably has an optimal value as well, given the system size, inertia, and reaction time.

The control algorithm described above has operated for over 1000 hours with penetration as high as 250%. It has performed well, though not perfectly. Problems have been identified concerning wind turbine soft starters, frequency transducers, and the time step for control decisions. Most of these have been driven by system hardware, rather than software issues. While somewhat tedious, the testing and selection of optimal control parameters is straight forward. Without hardware limitations like a slow, vulnerable frequency transducer, control optimization would have progressed much more quickly.

Acknowledgements:

Many thanks to Fang Jun Wang, who did the majority of the control programming in Labview, my collegue Ron Davis, and the interns that helped bring all the hardware into reality: Hubert Grimm, Jochen Schneider, Mark Michaelis, Matthias Langer, Michael Baumgart, Thomas Schips, Martin Assmann, Andreas Rapp, and Ralph Atallah.

WORKSHOP REPORT

AWEA
&
CanWEA

TWELTH ANNUAL INTERNATIONAL WIND-DIESEL WORKSHOP

JUNE 18-20, 1998

DUTCH INN
CHARLOTTETOWN
PRINCE EDWARD ISLAND
CANADA

Sponsored Jointly by the American and Canadian Wind Energy Associations
Assisted by Natural Resiources Canada and U.S. Department of Energy

To order additional copies contact AWEA at:
American Wind Energy Association, 122 C Street, 4th Floor, Washington, DC, 20001